An Overview of Grouting Developments

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Photograph 1. Excavated test columns created by one fluid (back center), two fluid (left) and three fluid (right front) systems. Courtesy of Rodio, Milan.

Rock grouting has been conducted in North America for almost a century and soil grouting is well into its fifth decade of application. However, for a number of well documented reasons (Reference 1), our practice has often been perceived as somehow lagging behind that of other countries. Recent developments, especially in mining and soft ground tunneling applications, plus the rapidly expanding volume of technical publications (Reference 2), conferences (Reference 3), and short courses would now seem to challenge that paradigm. These advances are indeed recent: it is only in 1991 that this magazine published an albeit pythesque article entitled "Equal Rights for Grouters" (Reference 4) in an oblique attempt to remind dam remediation engineers in particular of the overlooked benefits of contemporary drilling and grouting expertise. This very brief overview attempts to highlight the developments, and those responsible for them, as a framework for

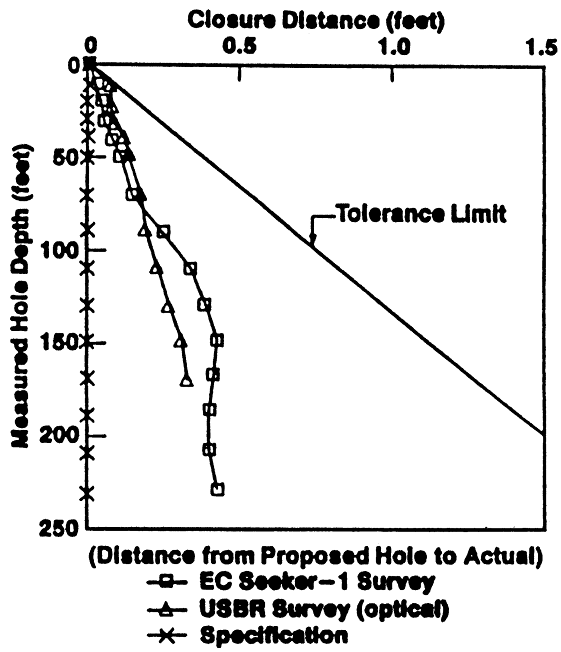


Figure 1. Data from monitoring of deep hole alignment. Stewart Mountain Dam, Arizona (Anchor Hole 37) (Reference 5)

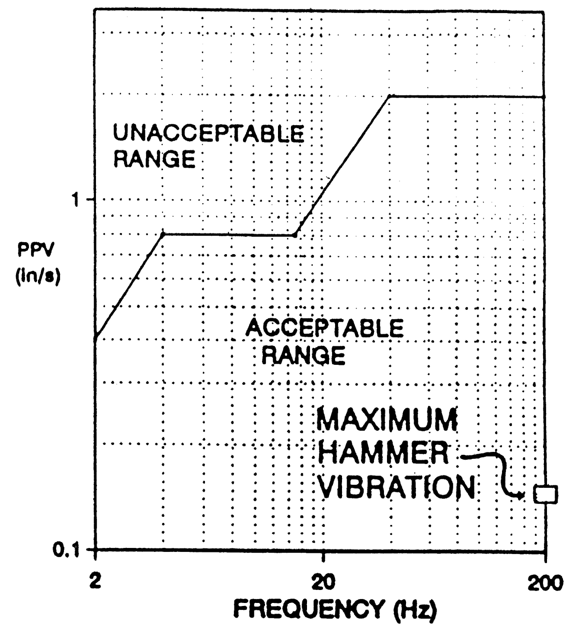


Figure 2 Vibration monitoring of structure 5 feet from drill hole location Stewart Mountain Dam, Arizona (Reference 5)

future research by the reader.

Rock Grouting

Rock grouting has basically two major applications - bulk grouting and fissure grouting. Regarding **bulk grouting**, there remains considerable activity in certain parts of the country where there is a need to infill natural cavities, such as sinkholes or karstic voids, and man-made cavities such as old mineral workings or abandoned underground structures. The development trends are simple: drill faster and cheaper, and inject with high productivity automated batching plants using local materials such as fly ash, wherever and as much as possible. Foam grouts are being developed to help extinguish mine fires.

In **fissure grouting**, however, there are many different developmental trends in the various processes (Reference 5). These include:

- Drilling - The use of high-powered diesel- or electro-hydraulic rigs, capable of either rotary or rotary percussive drilling modes and a variety of drill flush media. Monitoring has proved the ability of such rigs to drill very quickly and straightly (Figure 1) through rock and concrete while causing minimal mechanical damage to the surrounding structure (Figure 2). The performance of these rigs is often recorded electronically so that the "drillability" of the rock mass is automatically recorded. This is a very important quality assurance/quality control (QA/QC) feature.
- Grouting - more thought is being given to grout mix design and composition. The traditional "thin" mixes for so long favored by United States Federal agencies are being replaced by stable, modified cement-based grouts (References 6 and 7). In extreme water flow conditions such as may be found in deep mines, increasing use is being made of hot bitumen or water reactant prepolymer urethane grouts, as advocated by Mr. A. Naudts of ECO, in Toronto. In particularly difficult rock mass conditions where conventional up- or down-stage grouting cannot be used, the MPSP (Multiple Packer Sleeved Pipe) method is becoming popular (Figure 3, References 8 and 9).
- QA/QC - increasing attention is being paid to the automatic recording of grouting parameters. This may range from simple "in the field" chart records to the sophisticated, telemetric system, devised by the Bureau of Reclamation at the massive New Waddell Dam in Arizona (Reference 10). Such methods facilitate both control and analysis of grouting operations, a major feature of the "Responsive Integration" concept recently proposed (Reference 11).

Soil Grouting

We now recognize five categories of soil grouting and each has its own pace of development.

- Permeation grouting - involves placing grouts into the pre-existing pore without disturbing the virgin structure. A major trend, for economic, technical and environmental reasons, is the drift from chemical (solution) grouts to cement-based (particulate) grouts of special composition. Researchers into the latter category have revealed the fundamental controls of cement particle size, "viscosity," and internal stability (pressure filtration co-efficient) over the ability to penetrate fine-medium soils. These developments have led to grouts such as MISTRA and CEMILL which give excellent performance (Figure 4). In the interim,

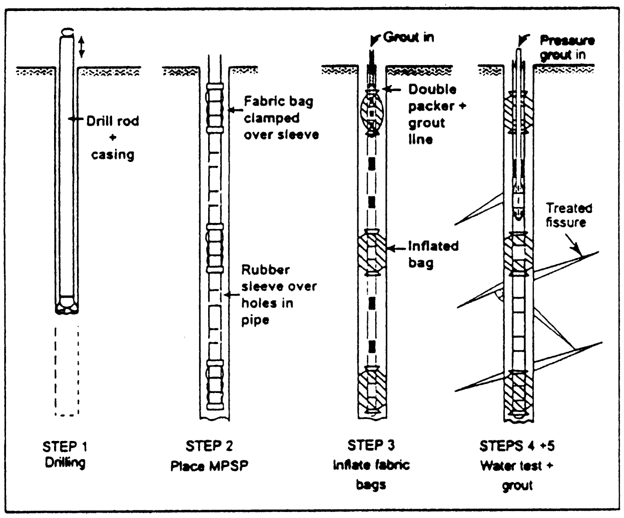


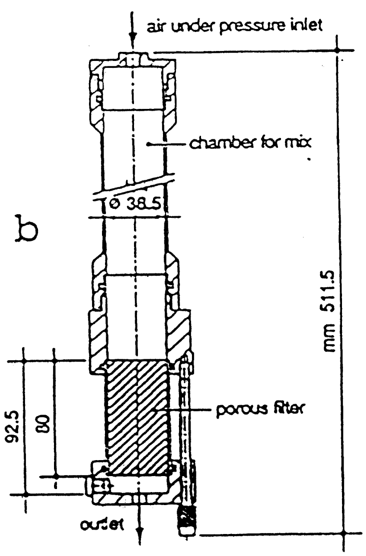
Figure 3. Installation steps of MPSP grouting method (Reference 9)

there remains considerable scope for stronger silicate gel grouts in the Metro works in Washington, D.C., San Francisco, and Los Angeles, in particular.

- Compaction grouting - this "uniquely American" process developed by Jim Warner in the early 1950s is now attracting an even wider range of applications. In summary, very stiff, "low mobility" grouts (Reference 12) are injected at high (4 MPa) grout pressures in predetermined patterns to increase the density of soft, loose, or disturbed soil. When appropriate materials and parameters are selected, the grout forms regular and controllable volumes. Near surface injections may result in the lifting of the ground surface and associated structures, akin to the principle of slabjacking (Reference 13), not further referred to in this article. New applications are being found in sinkhole rectification and seismic mitigation in embankment dams. Fun-

filter no.	permeability (m/s)		grain size (μm)					porosimetry (μm)							specific surface cm^2/g	retaining capacity (μm)
	theoretical Hazen (C = 1.45)	experim. (permeam.)	D 95	D 60	D 15	D 10	U	theoretical (Kozeny) D 80	D 50	D 30	experim. (Hg porosimetry) D 95	D 85	D 15	D10		
07	$5.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	1500	900	700	640	1.41	300	240	150	380	300	170	160	28	70
06	$2.3 \cdot 10^{-3}$	$8.3 \cdot 10^{-4}$	750	620	450	400	1.55	160	133	90	360	260	130	124	37	60
04	$7.7 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	700	480	250	230	2.09	110	90	60	300	140	70	64	56	40
01	$2.8 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	400	230	160	140	1.64	58	49	32	120	64	46	44	111	10
005	$1.4 \cdot 10^{-4}$	$9.5 \cdot 10^{-5}$	180	120	110	100	1.20	35	25	18	90	46	32	30	125	5

a



b

C

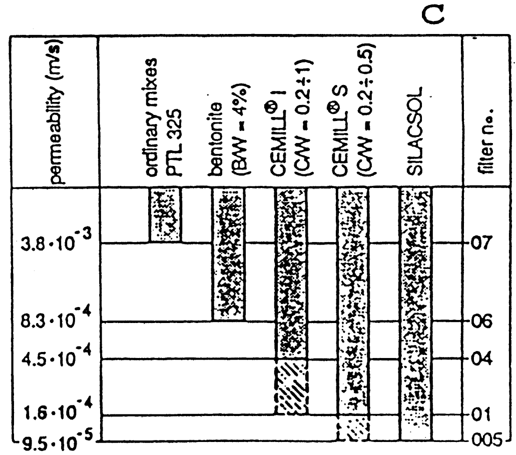


Figure 4. Injection test details: a) porous stone filter characteristics, b) apparatus, and c) penetrability limit of different mixes into filters.(Reference 20)

damental recent research has been conducted by Mr. Bandimere and colleagues at Denver Grouting Services in Denver and San Diego, which have far advanced knowledge of our abilities to design and construct compaction grouting work. Their technology is also being exported to Japan, Korea and Taiwan, a unique reversal of American fortunes.

- Hydrofracture grouting - the concept is that stable, high mobility cementitious grouts are injected at relatively high rates and pressures to deliberately fracture the ground. The lenses, ribbons and bulkheads of grout so formed are conceived as increasing total stresses, filling unconnected voids, locally consolidating or densifying the soil and providing a framework of impermeable membranes. It has been rare to find this principle deliberately exploited outside the French grouting industry, although there is no doubt that the effects have often been achieved, unintentionally, in the course of other methods of grouting: Warner, as noted above, has identified the possibility in compaction grouting operations, while Tornaghi et al. (Reference 14) note that hydrofracture naturally occurs with conventional cement-based grouts in soils with a permeability of less than 10-1 cm/sec. Graf (Reference 15) has described recent tests conducted in the U.S. towards rationalizing certain parameters. Apparently polypropylene fibers have been incorporated into the grout to provide a degree of tensile and flexural strength to the grout bodies after setting. In California especially, certain contractors are actively promoting the application of "controlled fracture" grouting for applications involving slope stabilization, loose fill consolidation, expansive soil treatment and soft ground tunneling. Despite the potential, the term "controlled fracture" remains nevertheless for many American grouting engineers a contradiction in terms.
- Jet grouting - the tremendous upsurge in jet grouting throughout the world since the late 1970s has been reflected only recently in North America. The earlier slow pace of work undertaken largely for underpinning (Reference 16) has now been changed by the demands of soft ground tunneling and deep excavations in heavily urbanized areas on the East and West Coasts. Jet grouting uses very high pressure cement grouts (up to 50 MPa) to erode and mix soils, transforming them into a grout/soil material of superior strength and permeability characteristics. Depending on the properties of the soil, and the injection parameters, grouted columns up to 3 m in diameter and up to 15 MPa unconfined compressive strength can be attained (Photograph 1). Two extremely significant projects have recently been conducted in the soft clays of Boston and San Francisco. In the former case, over 14,000 linear meters of columns were installed in the excavation for Contract CO7A1 of the Boston Central Artery Program, adjacent to Logan International Airport. Soil mixed wall (SMW) buttresses had been installed in the base of the 24 m deep excavation to provide basal stability, and as props and underpinning to the excavation walls (Figure 5). Due to space restrictions, these buttresses could not be placed immediately adjacent to the walls themselves, and so this connection was successfully and economically made by jet grouting (Reference 17).

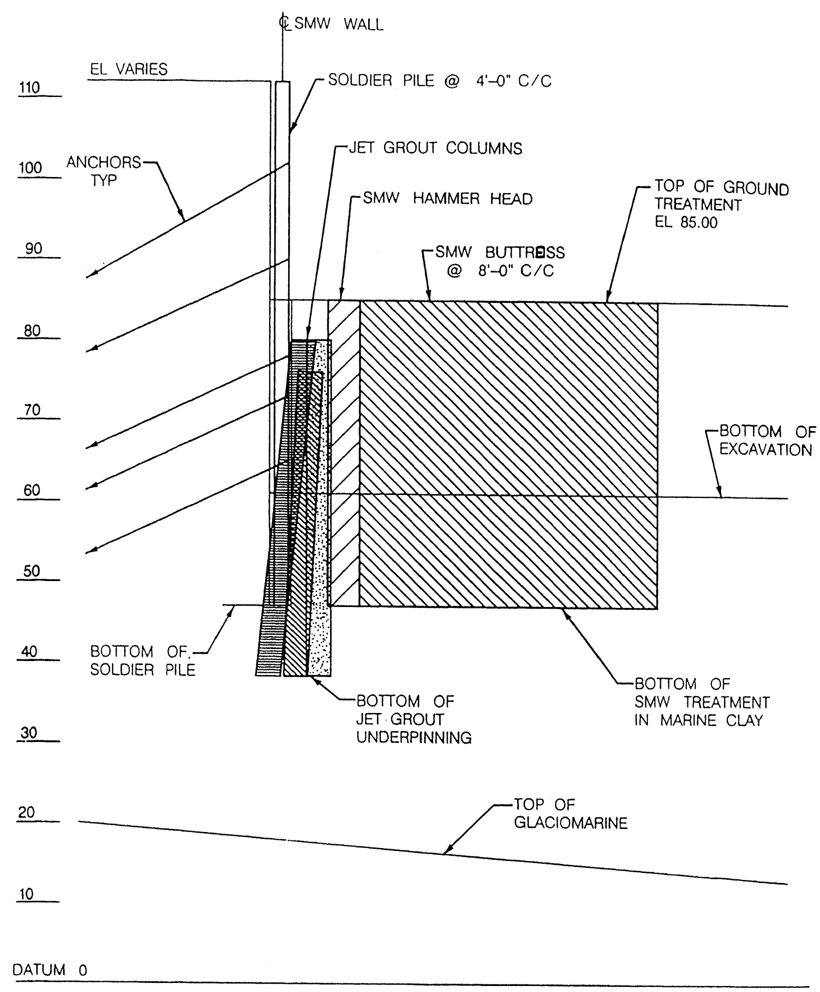


Figure 5. West Wall "Floating" SMW Buttress and Location of Jet Grouting (Reference 17)

In the latter case, the soils around a major new overflow tunnel 7 m in diameter were pretreated for a linear distance of over 300 m. This permitted the tunneling to be carved out by conventional methods without the need for compressed air or other systems typically used for safety or surface settlement concerns. In both cases, a full scale field test was conducted to verify the strength, shape and consistency of the columns, and the impact of various drilling and grouting parameters on these variables.

- Compensation grouting - this is essentially a major new exploitation, with appropriate "bells and whistles," of the principles of hydrofracture grouting (Reference 18) to eliminate surface settlements during soft ground tunneling. Prior to tunneling, the ground is treated, via the standard sleeve pipe (tube a manchette) system, with fairly mobile, cement-based grouts. During and/or after tunneling, the ground is reinjected via these same pipes to closely compensate for any loss of ground. An extremely high degree of injection control and surface monitoring is required. Major applications are underway in London during the construction of the new 2 billion pound Jubilee Underground Line, while a major North American example was recently completed by Hayward Baker for a tunneling project in Sarnia, Ontario (Reference 19).

Overview

To many eyes, the American grouting market is perceived as extremely conservative and invariably parochial. However, there are strong signs that things are changing. One can site the impact of foreign specialists, local "points of light," an active conference and training circuit, increasingly challenging applications and more enlightened contracting procedures. The consequence is that more grouting work is being conducted more effectively and with less legal intervention. This bodes well for the industry in the U.S., as it continues its path towards urban and industrial rehabilitation and infrastructure development and remediation.

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